USER'S GUIDE: RADIONUCLIDE CARCINOGENICITY

Introduction

EPA classifies all radionuclides as Group A carcinogens. The Radionuclide Table on this website, formerly HEAST Table 4, lists ingestion, inhalation and external exposure cancer slope factors (risk coefficients for total cancer morbidity) for radionuclides in conventional units of picocuries (pCi).(7) Ingestion and inhalation slope factors are central estimates in a linear model of the age-averaged, lifetime attributable radiation cancer incidence (fatal and nonfatal cancer) risk per unit of activity inhaled or ingested, expressed as risk/pCi. External exposure slope factors are central estimates of lifetime attributable radiation cancer incidence risk for each year of exposure to external radiation from photon-emitting radionuclides distributed uniformly in a thick layer of soil, and are expressed as risk/yr per pCi/gram soil. When combined with site-specific media concentration data and appropriate exposure assumptions(8), slope factors can be used to estimate lifetime cancer risks to members of the general population due to radionuclide exposures.

Intended Users and Applications

HEAST users include individuals from the EPA, other Federal agencies, States and contractors who are responsible for the identification, characterization and remediation of sites contaminated with radioactive materials. Radionuclide slope factors are calculated by EPA's Office of Radiation and Indoor Air (ORIA) to assist HEAST users with risk-related evaluations and decision-making at various stages of the remediation process. During site assessment, for example, slope factors are used in EPA's Hazard Ranking System (HRS) to assign toxicity factor values to radionuclides to calculate site scores. During the remedial investigation and feasibility study (RI/FS), slope factors are used to determine baseline site risk, to develop preliminary remediation goals, and to evaluate cleanup alternatives. For further examples on the application of radionuclide slope factors in risk evaluations, users are referred to the following EPA documents:

- Hazard Ranking System (HRS), Federal Register (55 FR 515320), December 1990.

- Risk Assessment Guidance for Superfund; Volume I - Human Health Evaluation Manual (RAGS/HHEM), Part A, Baseline Risk Assessment (EPA/540/1-89/002).

- RAGS/HHEM Part B, Development of Risk-Based Preliminary Remediation Goals OSWER Directive 9285.7-01B). [NTIS order number: PB 92-963333.]

- RAGS/HHEM Part C, Risk Evaluation of Remedial Alternatives (OSWER Directive 9285.7-01C). [NTIS order number: PB 92-963334.]

- Soil Screening Guidance for Radionuclides: User's Guide, October 2000. (OSWER Directive 9355.4-16A) **(note: The models, equations, and assumptions presented in the Soil Screening Guidance for Radionuclides supercede those described in RAGS HHEM, Part B, for residential soils.)**

Copies of RAGS/HHEM Parts A, B and C are available to the public from the National Technical Information Service (NTIS) at (703) 487-4650. Copies are available to EPA staff by calling the Superfund Documents Center at (703) 603-8917. The "Soil Screening Guidance for Radionuclides: User's Guide", is available at "http://www.epa.gov/superfund/resources/radiation/radssg.htm#user".

Radiation Effects

Ionizing radiation has been shown to be a carcinogen, a mutagen, and a teratogen. Radiation can induce cancers in nearly any tissue or organ in both humans and animals, and the probability of cancer induction increases with increasing radiation dose. Cancer induction is a delayed response that has been documented extensively in epidemiological studies of Japanese atomic bomb survivors, underground uranium miners, radium dial painters, and patients subject to a variety of radiation treatments. Laboratory animal research and mammalian tissue culture studies have provided additional, collaborative data.

Mutagenic effects of radiation have been demonstrated primarily in animal and tissue culture studies; limited data from studies of A-bomb survivors indicate that humans may be as sensitive or less sensitive than animals to radiogenic mutagenicity (heritable genetic mutations). Data are also available from both human and animal studies on the teratogenic effects of radiation. These data show that the fetus is most sensitive to radiation injury during the early stages of organ development (between 8 and 15 weeks for the human fetus). Resultant radiation-induced malformations depend on which cells are most actively differentiating at the time of exposure.

EPA classifies all radionuclides as Group A carcinogens, based on their property of emitting ionizing radiation and on the extensive weight of evidence provided by epidemiological studies of radiogenic cancers in humans. At Superfund radiation sites, EPA generally evaluates potential human health risks based on the radiotoxicity, i.e., adverse health effects caused by ionizing radiation, rather than on the chemical toxicity, of each radionuclide present (an exception is uranium, where both radiotoxicity and chemical toxicity are normally evaluated). These evaluations consider the carcinogenic effects of radionuclides only. In most cases, cancer risks are limiting, exceeding both mutagenic and teratogenic risks.

Derivation of Radionuclide Slope Factors

EPA's Office of Radiation and Indoor Air (ORIA) calculates radionuclide slope factor values using health effects data and dose and risk models from a number of national and international scientific advisory commissions and organizations, including the National Academy of Sciences (NAS), the

National Council on Radiation Protection and Measurements (NCRP), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the International Commission on Radiological Protection (ICRP). A detailed discussion of ORIA's approach and assumptions is provided in Estimating Radiogenic Cancer Risks (9).

Radionuclide slope factors are calculated for each radionuclide individually, based on its unique chemical, metabolic and radioactive properties. The calculation methodology is documented in Federal Guidance Report No. 13 (10). The risk coefficients derived in Federal Guidance Report No. 13, and used to calculate the slope factors presented in the Radionuclide Table, are based on state-of-the-art methods and models that take into account the age- and gender-dependence of radionuclide intake, metabolism, dosimetry, radiogenic risk, and competing causes of death in estimating the cancer risk from low-level exposures to radionuclides in the environment. The risk coefficients in Federal Guidance Report No. 13 are estimates of the probability of radiogenic cancer mortality (fatal cancers) or morbidity (fatal plus nonfatal cancers) per unit activity of a given radionuclide inhaled or ingested, for internal exposure, or per unit time-integrated activity concentration in air or soil, for external exposure. These risk coefficients may be interpreted either as the average risk per unit exposure for persons exposed throughout their lifetime to a constant activity concentration of a radionuclide in an environmental medium (air or soil), or as the average risk per unit exposure for persons exposed for a brief period to the radionuclide in an environmental medium. These risk coefficients are based on the age and gender distributions and the mortality characteristics of the 1989-91 U.S. decennial life tables.

Federal Guidance Report No. 13 tabulates risk coefficient values for both cancer mortality and cancer morbidity for six exposure pathways: inhalation, ingestion of tap water, ingestion of foodstuffs, external radiation from submersion in contaminated air, external radiation from radionuclides deposited on the ground surface, and external exposure from radionuclides uniformly distributed through soil. Additional risk coefficients are also provided for ingestion of milk for radioisotopes of iodine only. Inhalation risk coefficients are tabulated separately for each of the three lung absorption types considered in the lung model currently recommended by the International Commission on Radiological Protection (ICRP), and, where appropriate, for inhalation of radionuclides in vapor or gaseous forms. In order to maintain consistency with risk assessment algorithms presented in the RAGS documents referenced above, only four of these exposure pathways are tabulated in the Radionuclide Table: inhalation, water ingestion, food ingestion, and external exposure from radionuclides distributed in soil. One additional exposure pathway which is not directly considered in Federal Guidance Report No. 13, incidental ingestion of soil, is also included in the Radionuclide Table.(11) In addition, the values in the Radionuclide Table have been converted from the International System (SI) units used in Federal Guidance Report No. 13 to the conventional units of activity, again for greater consistency with the risk assessment algorithms in current guidance (e.g, RAGS).

The risk coefficients in Federal Guidance Report No. 13 are derived from the integration of four principal types of data:

- Absorbed dose rates for each tissue of interest (potential cancer site) over the remaining lifetime of an individual, resulting from an acute intake at a given age to the radionuclide of interest.

Age-specific estimates of absorbed dose rate are calculated for internal exposures (inhalation and ingestion), whereas absorbed dose rates calculated for a reference adult male are applied to all ages and both genders for external exposures.

- Age- and gender-specific risk coefficients, which express the lifetime excess cancer incidence risk per unit dose (e.g., expected cancer cases per unit absorbed dose) for specific cancer sites over the lifetime of the exposed population.

- For internal exposures only, age- and gender-specific usage data for the environmental medium of concern (e.g., inhalation rates and ingestion rates for water, food, and milk).

- Vital statistics and mortality data for the reference population (currently the 1989-1991 U.S. population), which define the survival function for an average member of the population - i.e., the probability of survival and projected years of life remaining at each age in the reference population, taking into account competing risks (mortality risks unrelated to radiation exposure, e.g., accidents, illness).

With a few exceptions, the dosimetry models for the inhalation and ingestion pathways are taken from ICRP Publication 72 (12) (which is a compilation of the ICRP's age-dependent dose coefficients for members of the public from intake of radionuclides), while dose rate estimates for external exposure pathways are taken from Federal Guidance Report No. 12 (13), which tabulates dose coefficients for external exposure to radionuclides in air, water, and soil. Since the criteria for the list of radionuclides considered in these two documents is not the same, risk coefficients for some radionuclides are not provided for all exposure pathways.

The radionuclide slope factors in the Radionuclide Table may be used to estimate the lifetime cancer incidence risk attributable to given radionuclide exposure conditions for an average member of the reference population. This estimate of excess risk is averaged over all ages and both genders for a population with specified mortality statistics (currently the U.S. population circa 1989-1991). These slope factors are appropriate for assessing the average risk within this population, but are not suitable for assessing the risk to a single individual of a particular age or gender. Estimates of radiogenic cancer risk are subject to numerous sources of uncertainty, including the biokinetic and dosimetric models, organ-specific risk factors, mortality and survival characteristics of the population, and the extrapolation of epidemiological data for populations exposed to high radiation doses to much lower levels characteristic of environmental exposures.

The slope factors are the average risk per unit intake or exposure for an individual in a stationary population with vital statistics (mortality rates) of the 1990 United States population. (The expected lifetime for an individual in this population is about 75 years.) Consequently, radionuclide ingestion and inhalation slope factors are not expressed as a function of body weight and time, and do not require corrections for GI absorption or lung transfer efficiencies.

NOTE: The GI absorption values (f1), ICRP lung absorption types (F, M, S) and radioactive half-lives are provided in the Radionuclide Table for reference only and should not be used to correct, modify, or in any way adjust radionuclide slope factors or intake assumptions in risk calculations.

The radionuclide slope factors tabulated in the Radionuclide Table are derived for the idealized conditions of chronic radionuclide intake or exposure, at a unit radionuclide concentration, throughout the lifetime of the exposed population. These values can be used in conjunction with site-specific data describing the concentrations of radionuclides of concern in environmental media (e.g., air, water, vegetation, soil, and foodstuffs) and with information describing the exposure conditions (e.g., inhalation and ingestion rates; exposure times, frequencies and durations; etc.) to estimate the cancer risk from inhaling contaminated air, eating contaminated food or soil, drinking contaminated water, or from external exposure to contaminated ground surfaces for given site conditions. Whether for inhalation, ingestion, or external exposure, the lifetime excess risk is related to the cumulative intake or exposure to the given radionuclide:

For inhalation and ingestion, the total radioactivity (pCi) inhaled or ingested must be known.

For external exposure, the integral of the product of the soil concentration of each radionuclide of interest and the total duration of exposure in the contaminated area (pCi-y per gram of soil) must be known, considering the effect of shielding provided by buildings or other site features. Note that the soil concentration of each radionuclide of concern may vary over time as a result of the radioactive decay process - i.e., concentrations of some radionuclides may decrease over time due to radioactive decay whereas concentrations of other radionuclides may increase due to ingrowth of radioactive decay products. Also, the effect of shielding afforded by buildings during periods of indoor occupancy or other site features must be considered explicitly, because the slope factors are derived for conditions of outdoor exposure without shielding.

For each radionuclide and exposure pathway, the excess cancer risk is estimated as the product of the slope factor and the cumulative intake or external exposure. The risks presented by each radionuclide (including radioactive decay products) and exposure pathway in a given exposure situation should be assessed separately and summed to estimate the total radiation risk.

About the Information Provided in the Radionuclide Table

The Radionuclide Table lists ingestion, inhalation and external exposure slope factors for principal radionuclides, and provides key parameter values used in the derivation of slope factor values. Radionuclides are presented alphabetically by element and atomic weight.

Selected radionuclides and radioactive decay chain products are designated in the Radionuclide Table with the suffix "+D" (e.g., U-238+D, Ra-226+D, Cs-137+D) to indicate that cancer risk estimates for these radionuclides include the contributions from their short-lived decay products, assuming equal activity concentrations (i.e., secular equilibrium) with the principal or parent nuclide in the environment.(14) Decay chains for these radionuclides are identified in Exhibit 1. For all radionuclides without the "+D" suffix, only intake or external exposure to the single radionuclide is considered. For inhalation and ingestion pathways, the contribution to dose and radiogenic cancer risk from all radioactive decay products formed in the body after intake of the parent radionuclide is explicitly included in the risk coefficient values; however, only the parent radionuclide is assumed to be ingested or inhaled.

In most cases, site-specific analytical data should be used to establish the actual degree of equilibrium between each parent radionuclide and its decay products in each media sampled. However, in the absence of empirical data, the "+D" values for radionuclides should be used unless there are compelling reasons to do otherwise. For example, the external slope factors for Cs-137 and Cs-137+D are 5.32 x 10-10 and 2.55 x 10-6 (risk per year per pCi/gram), respectively. The value for Cs-137+D is higher because it includes the risk contribution from Cs-137's short-lived gamma-emitting decay product Ba-137m (half-life, 2.55 minutes) which, under most environmental conditions, will be in secular equilibrium with Cs-137.

Note that there may be circumstances, such as long disposal times or technologically enhanced concentrations of naturally occurring radionuclides, that necessitate the combination of the risks of a parent radionuclide and its decay products over several contiguous subchains. For example, Ra-226 soil analyses at a site might show that all radium decay products are present in secular equilibrium down to stable Pb-206 (See Exhibit 1). In this case, Ra-226 risk calculations should be based on the ingestion, inhalation and external exposure slope factors for the Ra-226+D subchain, plus the ingestion, inhalation and external exposure factors for the Pb-210+D subchain. For actual sites, users should consult with a health physicist or radiochemist (1) to evaluate the site-specific analytical data to determine the degree of equilibrium between parent radionuclides and decay members of contiguous decay chains and (2) to assist in the combination of appropriate slope factor values. For health physics and radioanalytical support, users may contact EPA's Regional Radiation Program Managers, ORIA's National Air and Radiation Laboratory (NAREL) in Montgomery, Alabama, ORIA's Las Vegas Laboratory (ORIA-LV) in Las Vegas, Nevada, or the ORIA contact at EPA headquarters in Washington, D.C.

A Chemical Abstract System Reference Number (CASRN) is provided for each radionuclide for which a number has been assigned, for identification and reporting accuracy during risk assessments; for radionuclides for which CASRN numbers have not yet been assigned, the value is designated as "NA". The radioactive half-life of each radionuclide is also provided for reference.

The designations "F", "M", and "S" presented in the Radionuclide Table under the heading "ICRP Lung Type" refer to the lung absorption type for inhaled particulate radionuclides, expressed as fast (F), medium (M), or slow (S), as used in the current ICRP model of the respiratory tract. The inhalation slope factor value tabulated in the Radionuclide Table for each radionuclide have been selected based on the following guidelines: (1) For those elements where Table 4.1 of Federal

Guidance Report No. 13 (and Table 2 of ICRP Publication 72) specifies a recommended default lung absorption type for particulates, the inhalation slope factor for that type is tabulated in the Radionuclide Table for each radioisotope of that element. (2) For those elements where no specific lung absorption type is recommended and multiple types are indicated as plausible choices, the inhalation slope factor reported in the Radionuclide Table for each radioisotope of that element is the maximum of the values for each of the plausible lung absorption types. (3) Where Federal Guidance Report No. 13 specifies risk coefficients for multiple chemical forms of certain elements (tritium, carbon, sulfur, iodine, and mercury), the inhalation slope factor value for the form estimated to pose the maximum risk is reported in the Radionuclide Table in most cases.(15)

Inhaled particulates are assumed to have an activity median aerodynamic diameter (AMAD) of 1 um, as recommended by the ICRP for consideration of environmental exposures in the absence specific information physical characteristics of the aerosol. Where appropriate, radionuclides may be present in gas or vapor form, are designated by "G" and "V", respectively; such radionuclides include tritium, carbon, sulfur, nickel, ruthenium, iodine, tellurium, and mercury.

"GI Absorption Fractions (f1)" are the fractional amounts of each radionuclide that may be absorbed from the gastrointestinal (GI) tract into blood following an oral intake. Separate slope factor values are presented in the Radionuclide Table for ingestion of drinking water, food, and soil. These values have been derived using the same dosimetry and risk models, but different age-specific intake rate functions. Federal Guidance Report No. 13 specifies ingestion risk coefficients for multiple chemical forms of tritium, sulfur, mercury, and polonium. For radioisotopes of mercury, the slope factor value for the chemical form estimated to pose the maximum risk is reported in the Radionuclide Table for each of the ingestion pathways. For tritium, values for ingestion of both tritiated water and organically bound forms of tritium are tabulated in the Radionuclide Table, because tritiated water is considered to be the prevalent form for most environmental exposures but the slope factor values for ingestion of organically bound forms of H-3 are estimated to produce a greater risk per unit intake. For radioisotopes of sulfur and polonium, Federal Guidance Report No. 13 provides values for ingestion of organic and inorganic compounds; for these radionuclides, the value for ingestion of organic compounds is assumed for ingestion of food, while the value for ingestion of inorganic forms is assumed for ingestion of water or soil. For radioisotopes of iodine, slope factor values for ingestion of milk are greater than the corresponding values for ingestion of other dietary intakes in all cases, and these values are reported under the "Food Ingestion" column in the Radionuclide Table.

The ICRP lung absorption types and GI absorption factors provided in the Radionuclide Table are the default values that EPA has used to calculate radionuclide slope factors for inhalation and ingestion exposures, respectively. These factors are provided for reference only.

Where to Address Questions About Radionuclide Slope Factors:

EPA continuously reviews the scientific literature on radiation effects to ensure that the Agency's risk assessment methodologies are consistent with current models and assumptions. As risk methodologies are refined, EPA will revise and update the slope factors in the Radionuclide Table.

HEAST users with questions about radionuclide slope factor values and their use in radiation risk assessments should contact Phillip Newkirk of the Center for Radiation Site Cleanup at ORIA at (202) 564-9377. Written requests for assistance can be sent by fax to (202) 565-2042.

Exhibit 1. Radionuclide Decay Chains Considered Explicitly in the Radionuclide Table(16)

Principal Radionuclide [(a)]			Terminal Nuclide or Radionuclide [(c)]	
Nuclide	Half-life (yr)	Associated Decay Chain [(b)]	Nuclide	Half-life (yr)
Ac-227+D	22	[Th-227 (98.62%, 19 d)] Fr-223 (1.38%, 22 min) Ra-223 (11 d) Rn-219 (4 s) Po-215 (2 ms) Pb-211 (36 min) Bi-211 (2 min) [Tl-207 (99.72%, 5 min) Po-211 (0.28%, 0.5 s)]	Pb-207	*
Am-242m+D	152	Am-242 (99.52%, 16 h) Cm-242 (82.70%, 162 d) Np-238 (0.48%, 2.12 d)	Pu-238	87.7
Am-243+D	7.4×10^3	Np-239 (2.36 d)	Pu-239	2.4×10^4
Ce-144+D	0.8	[Pr-144 (98.22%, 17 min) Pr-144m (1.78%, 7 min)]	Nd-144	*
Cs-137+D	30	Ba-137m (94.6%, 3 min)	Ba-137	*
Np-237+D	2.1×10^6	Pa-233 (27 d)	u-233	1.6×10^5
Pb-210+D	22	Bi-210 (5 d) Po-210 (138 d)	Pb-206	*
Pu-244+D	8.3×10^7	U-240 (14 h) Np-240m (7.4	Pu-240	6.5×10^3
Ra-226+D	1.6×10^3	Rn-222 (4 d) Po-218 (3 min) [Pb-214 (99.98%, 27 min) At-218 (0.02%, 2 s)] Bi-214 (99.99%, 20 min) [Po-214 (99.98%, 1.64 x 10-4 s) Tl-210 (0.02%, 1 min)]	Pb-210	22
Ra-228+D	6	Ac-228 (6h)	Th-228	2

Principal Radionuclide [a]			Terminal Nuclide or Radionuclide [c]	
Nuclide	Half-life (yr)	Associated Decay Chain [b]	Nuclide	Half-life (yr)
Ru-106+D	1	Rh-106 (30s)	Pd-106	*
Sb-125+D	3	Te-125m (22.8%, 58d)	Te-125	*
Sr-90+D	29	Y-90 (64h)	Zr-90	*
Th-228+D	1.9	Ra-224 (4 d) Rn-220 (56 s) Po-216 (0.2 s) Pb-212 (11 h) Bi-212 (61 min) [Po-212 (64.07%, 0.3 s) Tl-208 (35.93%, 3 min)]	Pb-208	*
Th-229+D	7.3×10^3	Ra-225 (15 d) Ac-225 (10 d) Fr-221 (5 min) At-217 (32 ms) Bi-213 (46 min) [Po-213 (97.8%, 4 s) Tl-209 (2.2%, 2 min)] Pd-209 (3 h)	Bi-209	*
U-235	7.0×10^8	Th-231 (26 h)	Pa-231	3.3×10^4
U-238+D	4.5×10^9	Th-234 (24 d) [Pa-234m (99.80%, 1 min) Pa-234 (0.33%, 7 h)]	U-234	2.4×10^5

(a) Radionuclides with half-lives greater than six months. "+D" designates principal radionuclides with associated decay chains.

(b) The chain of decay products of a principal radionuclide extending to (but not including) the next principal radionuclide or a stable radionuclide. Half-lives are given in parentheses. Branches are indicated by square brackets with branching percentages in parentheses.

(c) The principal radionuclide or stable nuclide that terminates an associated decay chain. Stable nuclides are indicated by an asterisk (*) in place of a half-life.

(d) A hyphen indicates that there are no associated decay products.

ENDNOTES

1. Eckerman, K.F., Leggett, R.W., Nelson, C.B., Puskin, J.S., and Richardson, A.C.B. (1999). Cancer Risk Coefficients for Environmental Exposure to Radionuclides. Federal Guidance Report No. 13. EPA 402-R-99-001.

2. Soil ingestion is not considered as an exposure pathway in Federal Guidance Report No. 13. The slope factor values reported in Table 4 for soil ingestion have been computed using the same calculational methodology (i.e., the DCAL computer code developed at Oak Ridge National Laboratory), risk models, and vital statistics, in conjunction with the default soil ingestion rate specified in EPA's Risk Assessment Guidance for Superfund (RAGS), i.e., 200 mg/day from birth to age 6, and 100 mg/day for ages >6 years.

3. Nelson, C.B. and Puskin, J.S. (1994). Estimating Radiogenic Cancer Risk. EPA 402-R-93-076.

4. International Commission on Radiological Protection (ICRP). (1996). Human Respiratory Tract Model for Radiological Protection. ICRP Publication 66.

5. Eckerman, K.F., and J.C. Ryman (1993). External Exposure to Radionuclides In Air, Water, and Soil. Federal Guidance Report No. 12. EPA 402-R-93-081.

6. EPA (1997). OSWER Directive 9200.4-18, Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination.

7. Slope factors are reported in the Radionuclide Table in the customary units of picocuries (1 pCi = 10-12 curies (Ci) = 3.7x10-2 nuclear transformations per second) for consistency with the previous versions of HEAST. If required, slope factors in the Radionuclide Table can be converted into the International System (SI) units of becquerels (1 Bq = 1 nuclear transformation per second) by dividing each inhalation, ingestion, or external exposure value by 0.037. Users can calculate cancer risks using slope factors expressed in either customary units or SI units with equivalent results, provided that they also use air, water and soil concentration values in the same system of units.

8. Agency standardized default exposure scenarios and assumptions for use in baseline risk assessment are provided in EPA (1991), Risk Assessment Guidance for Superfund, Vol. I, Human Health Evaluation Manual, Supplemental Guidance: "Standard Default Exposure Factors" (Interim Final), Office of Emergency and Remedial Response, OSWER Directive 9285.6-03. [NTIS order number: PB 91-921314.]

9. Nelson, C.B. and Puskin, J.S., (1994). Estimating Radiogenic Cancer Risk, EPA 402-R-93-076.

10. Eckerman, K.F., Leggett, R.W., Nelson, C.B., Puskin, J.S., and Richardson, A.C.B. (1999). "Cancer Risk Coefficients for Environmental Exposure to Radionuclides," EPA 402-R-99-001.

11. Soil ingestion is not considered as an exposure pathway in Federal Guidance Report No. 13. The slope factor values reported in the Radionuclide Table for soil ingestion have been computed using the same calculational methodology (i.e., the DCAL computer code developed at Oak Ridge National Laboratory), risk models, and vital statistics, in conjunction with the default soil ingestion rate specified in EPA's Risk Assessment Guidance for Superfund (RAGS), i.e., 200 mg/day from birth to age 6, and 100 mg/day for ages >6 years.

12. International Commission on Radiological Protection, (1996), Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 5, Compilation of Ingestion and Inhalation Dose Coefficients, ICRP Publication 72.

13. Eckerman, K.F. and J.C. Ryman, (1993), External Exposure to Radionuclides in Air, Water, and Soil, Federal Guidance Report No. 12, EPA 402-R-93-081.

14. There is one exception to the assumption of secular equilibrium. For the inhalation slope factor for Rn-222+D reported in the Radionuclide Table, ORIA assumes a 50% equilibrium value for radon decay products (Po-218, Pb-214, Bi-214 and Po-214) in air. [NOTE: EPA expects to publish revised risk estimates for inhalation of radon decay products in the near future, based on a revised equilibrium assumption of 40%.]

15. An exception is tritium, H-3, where the value for inhalation of tritiated water vapor is reported in the Radionuclide Table, even though this value is less than that from inhalation of H-3 in particulate form or organic gases, because this form is expected to be most common in the environment.

16. Source: International Commission on Radiological Protection (1983). Radionuclide Transformations: Energy and Intensity of Emission, ICRP Publication 38, Annals of the ICRP, Vols. 11-13, Pergamon Press, New York, NY.